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Erodibility and infiltration characteristics of five major soils of southwest Spain

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Abstract

Equations used to calculate erodibility in the Water Erosion Prediction Project soil erosion model (WEPP) are based on erodibility studies in the USA and may not function well in another region. This study was conducted to: (i) analyze erodibility and infiltration characteristics of some predominant soils of southern Spain, and (ii) test equations used to calculate interrill erodibility in the WEPP model on these soils. The five soils chosen for this study in Andalusia, southwest Spain, were: two terrace soils (referred to as 'Red and Yellow Alfisols'), an alluvial soil ('Fluvent'), a shallow hillside soil ('Inceptisol'), and a cracking clay soil ('Vertisol'). A static, solenoid operated rainfall simulator was operated at an intensity of approximately 60 mm h^{-1} during a 60-min dry run followed by a 30-min wet run the next day on 0.75 m^2 plots with 30% ridge slopes. Infiltration rates were high (always exceeding 50% except for the wet run of the Fluvent). The Fluvent had the lowest infiltration rate (0.00 mm min^{-1} at the end of the wet run) and highest soil loss (985 g m^{-2} h^{-1} in the dry run and 1557 g m^{-2} h^{-1} in the wet run). The Vertisol, Inceptisol and Red Alfisol had low soil loss (415, 605, and 527 g m^{-2} h^{-1} in the dry run and 824, 762 and 629 g m^{-2} h^{-1} in the wet run, respectively). Soil loss of the Vertisol doubled between dry and wet run and infiltration rate did not stabilize, suggesting that erodibility of Vertisols increases when they are wet. The Yellow Alfisol had lower final infiltration rate in the dry run (0.33 mm min^{-1}) than in the wet run (0.58 mm min^{-1}) and higher soil loss in dry run (1203 g m^{-2} h^{-1}) than in wet run (961 g m^{-2} h^{-1}), the reason still being unclear. Soil loss was significantly correlated to silt + very fine sand content ($r = 0.96$), indicating that erodibility of these soils is determined by similar properties as soils in these soil orders in the USA. However,

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the equation for WEPP-interrill erodibility overestimated erodibility significantly (two to four times), indicating the need to develop new erodibility equations for the Mediterranean region. Infiltration rates were generally high and soil loss rates low compared to reports from the USA, suggesting that limited runoff generation is a primary reason for low erodibility of these soils.

Keywords: Mediterranean region; Runoff; Infiltration; Soil erosion; Water erosion prediction project

1. Introduction

Soil erosion is the major cause of soil degradation in Spain, especially in Andalusia (southwest Spain). Forty percent of the land in Andalusia has lost the A and part of the B horizons due to soil erosion by water (Conacher and Sala, 1998). Eighty percent of watersheds of hydrological reservoirs in the Guadalquivir River have erosion rates exceeding 20 Mg ha^{-1} $year^{-1}$ (Conacher and Sala, 1998). High priority should be given to soil conservation to reduce these unsustainable soil loss rates. To design and evaluate soil conservation practices, soil erosion models are needed that are calibrated for this region. However, no calibrated soil erosion model is as yet available. When soil erosion estimates are needed to determine sedimentation rates of reservoirs or to develop soil conservation strategies, use is mostly made of soil erosion models developed under North American conditions (ICONA, 1987; Albaladejo et al., 1993; Junta de Andalucía, 1995).

One factor in erosion models is the erodibility of the soil. Erodibility depends on the primary particle distribution, how strongly these primary particles are aggregated together, and whether runoff occurs during a rain shower. In erosion models, these parameters need to be related to easily measured soil properties. In the empirical Universal Soil Loss Equation (USLE), erodibility of a soil is calculated based on soil texture, organic matter content, structural group, and permeability class (Wischmeier and Smith, 1978). In the process based Water Erosion Prediction Model (WEPP, Flanagan and Nearing, 1995), baseline interrill erodibility is calculated based on soil texture factors only (Alberts et al., 1995). Clay usually decreases erodibility, as observed in studies in different parts of the world (Kemper and Koch, 1966; Imeson and Verstraten, 1989; Dimoyiannis et al., 1998). Organic matter increases aggregate stability and resistance to erosion (Kemper and Koch, 1966). Other properties, which may influence erodibility, include finely divided calcium carbonate, iron and aluminum oxides, and parent material (Middleton, 1930; Lutz, 1936; De Meester and Jungerius, 1978; Trott and Singer, 1983; Goldberg et al., 1988; Cerdà, 1996).

Some studies suggest that erodibility of soils of the Mediterranean region is much lower than that of soils in the USA (Roose et al., 1993; Poesen and Hooke, 1997). This would be due to as yet unknown properties of Mediterranean soils. In the present study, soils from the major soil orders of southern Spain, developed in three different parent materials, were subjected to simulated rainfall to: (i) determine interrill erodibility and infiltration characteristics of some important agricultural soils of southern Spain, and (ii) test empirical relationships of soil interrill erodibility developed in the USA on those soils. The hypotheses tested were: (i) interrill erodibility of soils from Spain and the

USA is controlled by similar soil properties, and (ii) the equations to calculate interrill erodibility in the WEPP model are applicable to the soils of Spain.

2. Materials and methods

2.1. Soil analyses

The experimental sites were located on the experimental farm "Rabanales" of the Universidad de Córdoba (long 4°43′E and lat 37°55′N) (Fig. 1). Five soils were selected representing the four major soil orders of the Mediterranean region (Torrent, 1995), derived from three different parent materials. Soil samples were collected from the 0–10 cm depth around the plot areas. The particle size distribution was determined after shaking overnight in 2.5 g L^{-1} sodium hexametaphosphate using sieving and pipette methods (Gee and Bauder, 1986). Soil pH was measured in a 1:1 water to soil mixture (McLean, 1982), and citrate/bicarbonate/dithionite extractable iron (Fe_d) with the

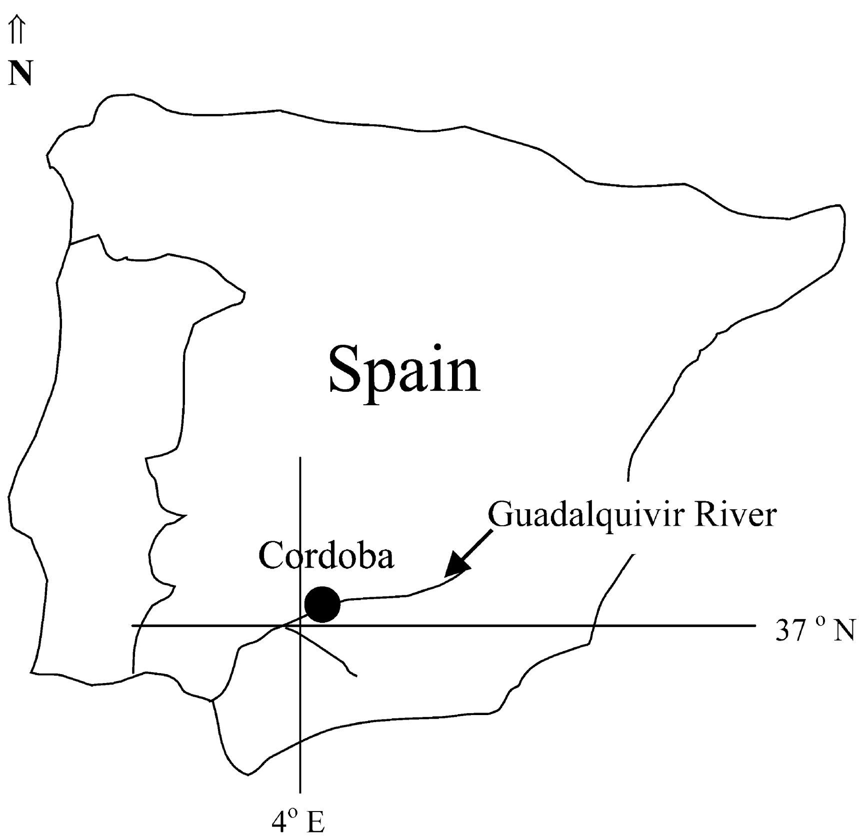


Fig. 1. Location of rainfall simulation experiment.

method of Mehra and Jackson (1960). The organic matter content was analyzed with the Walkley–Black procedure (Nelson and Sommers, 1982), and the cation exchange capacity (CEC, pH = 7) after extraction with ammonium acetate and sodium chloride (National Soil Survey Center, 1996). The exchangeable bases were determined in the ammonium acetate extract by atomic absorption spectrometry (Baker and Suhr, 1982).

2.2. Rainfall simulation

Rainfall simulation experiments were conducted from August to October 1998. On each soil, three plots of 75×100 cm were prepared in the shape of two row sides having slopes of approximately 30% (Table 1), conforming to WEPP methodology (Elliott et al., 1989). Soils with a minimum of coarse elements were selected in this study. The top 15 cm of the soil was mixed with a spade and big clods were crushed to create a smooth surface. Crop residue, root biomass and gravel > 4 cm were removed from the plots before rainfall simulation. A metal trough in the plot centre (on average 7.5 cm wide) was used to channel sediment and runoff from the row sides to a small collection pit. Runoff and sediment were collected at 5-min intervals in plastic containers, weighed, dried at 50°C, and weighed again to determine runoff volume and soil loss. Sediment remaining in the trough after termination of rainfall simulation runs was also collected and dried to calculate total soil loss. Runoff depth was calculated by dividing the volume of runoff by the plot area, after correcting for rainfall on the metal trough and the area of the trough. Infiltration was calculated by difference from runoff and rainfall intensity.

A static, solenoid operated rainfall simulator was used as described by Miller (1987, Fig. 2). A Spraying System wide square nozzle WSQ50 was operated at a gauge pressure of approximately 50 kPa, using well water with an electrical conductivity of 0.2–0.5 dS m^{-1}. This electrical conductivity is comparable to that used in the WEPP soil erosion studies (Elliot et al., 1989). The nozzle was located at a height of 260 ± 5

Table 1
Details of rainfall simulation runs
Standard error of mean between brackets.

Soil	Run	No. of reps	Rainfall intensity (mm h^{-1})	Initial soil wetness (g g^{-1})	Average ridge slope (%)	Time incipient runoff (min)
Red Alfisol	Dry run	2	59 (0.9)	0.15 (0.02)	29 (1.0)	15 (0.5)
	Wet run	2	56 (0.6)	0.23 (0.00)		5 (nd)
Yellow Alfisol	Dry run	3	66 (1.7)	0.03 (0.00)	32 (1.4)	19 (0.7)
	Wet run	2	62 (0.9)	0.21 (0.00)		2 (0.5)
Fluvent	Dry run	3	59 (1.7)	0.02 (0.00)	30 (2.1)	12 (1.8)
	Wet run	3	60 (0.5)	0.19 (0.01)		2 (0.6)
Inceptisol	Dry run	2	64 (1.9)	0.04 (0.00)	26 (0.9)	16 (nd)
	Wet run	2	59 (1.4)	0.24 (0.01)		6 (1.8)
Vertisol	Dry run	3	59 (2.0)	0.06 (0.00)	no data	24 (4.5)
	Wet run	2	58 (1.0)	0.30 (0.03)		8 (0.0)

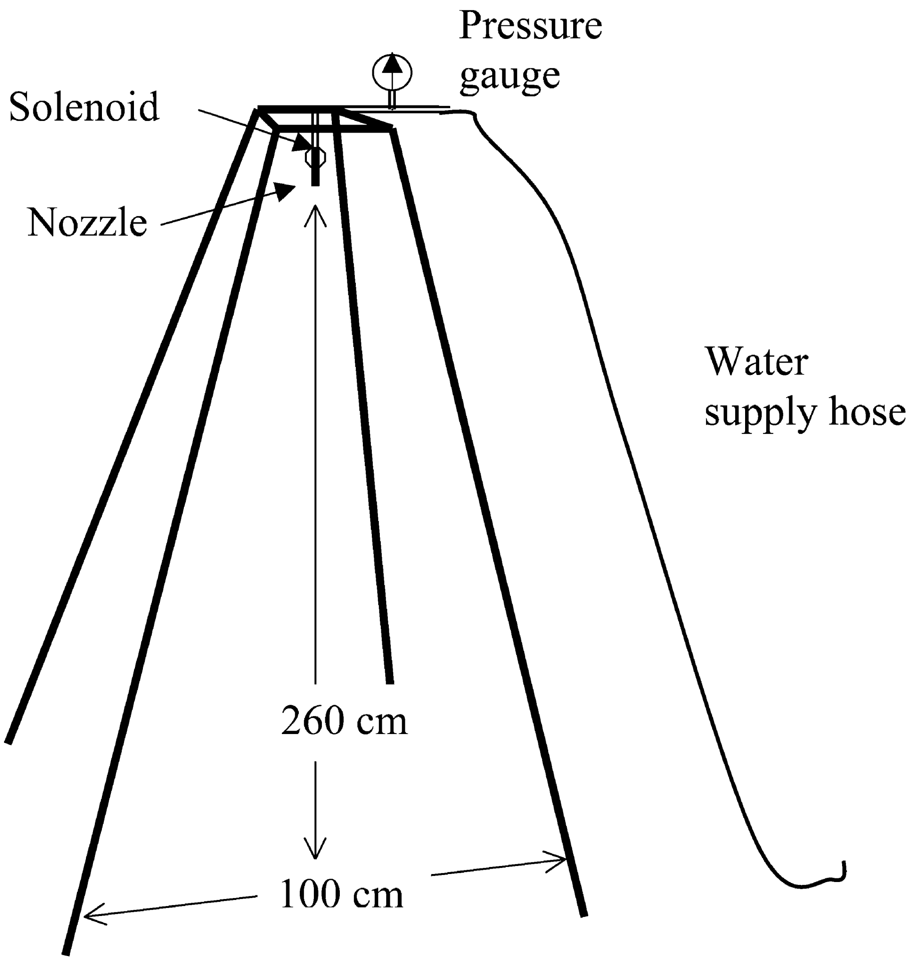


Fig. 2. Rainfall simulator used in this experiment.

cm above the centre of the plot, spraying at an intensity of approximately 60 mm h^{-1}. Although the rainfall intensity and the erosivity of the simulated rainstorm (between 900 and 1000 MJ mm ha^{-1} h^{-1}) were high compared to natural rainfall records for Córdoba (Giráldez et al., 1989), they were modest compared to other reports from the Mediterranean region (Poesen and Hooke, 1997).

The nozzle operated at the pressure and height used in this experiment produced rain drop size distribution and terminal velocities similar to those reported for natural rains (Shelton et al., 1985). It is, therefore, believed that the results can be safely compared to other interrill erodibility studies with rainfall simulators simulating the drop size distribution and terminal velocities of natural rain. Uniformity coefficients $100 \times [1 - \{\Sigma|x_i - (\Sigma x_i/n)|/\Sigma x_i\}]$ during calibration runs were between 89% and 91% and coefficients of variation were between 11% and 17%. This uniformity of rainfall is high compared to other rainfall simulation studies (see, for example, Morin et al., 1967; Meyer and Harmon, 1979; Bubenzer et al., 1985). Actual rainfall intensity (Table 1) and uniformity (not shown) were monitored using four cups placed at the borders of the plot. Rainfall simulation runs were done in triplicate. Runs with unacceptable uniformity coefficients were excluded from the analysis. A dry run of 60 min was followed by a 30-min wet run on the same plot approximately 24 h later.

2.3. Calculations and statistical analyses

WEPP interrill erodibility (K_i) was calculated from runoff and soil loss rates of the final three 5 min periods of each run (Foster et al., 1995):

$$D_i = K_{iadj} \times I_e \times \sigma_{ir}$$

where D_i = detachment capacity by interrill flow (kg s^{-1} m^{-2}); K_{iadj} = WEPP-K_i × [1.05 − 0.85 exp(−4sin Ω)]; WEPP-K_i = interrill erodibility (kg s^{-1} m^{-2}); Ω = average ridge slope angle (degrees); I_e = effective rainfall intensity (m s^{-1}); σ_{ir} = interrill runoff rate (m s^{-1}). Calculated WEPP-K_i was determined with the equations (Alberts et al., 1995):

$$K_i = 2{,}728{,}000 + 192{,}100 \times \text{vfs},$$

for soils containing 30% or more sand where vfs = percent very fine sand content (0.05–0.1 mm diameter), and:

$$K_i = 6{,}054{,}000 - 55{,}130 \times \text{clay},$$

for soils containing less than 30 % sand where clay = percent clay content ($<$ 0.002 mm).

Results were analyzed with SAS version 6.12 (SAS, 1989).

3. Results

3.1. Soil characteristics

The soils selected were two Alfisols, two Inceptisols, and a Vertisol (Table 2). In this paper, these soils are subsequently referred to as: Red and Yellow Alfisol, Fluvent, Inceptisol, and Vertisol. The Red and Yellow Alfisols both formed in old terraces of the Guadalquivir River, and had sandy surface horizons. The color of these Alfisols indicated that the crystalline iron oxide hematite was present in the Red Alfisol, but virtually absent in the Yellow Alfisol. The Fluvent developed from the silt and fine sand alluvium deposited by a small creek. The Inceptisol was a young, shallow soil developed in-situ from marl and had fairly high clay content. The Vertisol was a colluvial cracking clay soil developed downslope from the Inceptisol. All soils had been in annual crops

Table 2
Description of soils of this study

Soil classification[a]	Soil nickname	Geology and slope	Former land use
Thermic, montmorillonitic, fine Calcic Palexeralf (Chromic Luvisol)	Red Alfisol	Red soil developed on terrace of Guadalquivir. Well drained, frequent stones and gravel in surface horizons. Slope 1%	Maize, *Zea mays* L.
Thermic, montmorillonitic, clayey Aquic Palexeralf (Eutric Planosol)	Yellow Alfisol	Yellow soil developed on terrace of Guadalquivir. Moderately well drained. Slope 2%	Cultivated Fallow
Thermic, silicic, fine loamy Fluventic Xerochrept (Eutric Cambisol)	Fluvent	Alluvial soil at 20 m from stream. Well drained. Carbonates only in surface horizon. Slope 0%	Wheat, *Triticum aestivum* L.
Thermic, calcic, montmorillonitic, fine Calcixerollic Xerochrept (Calcaric Cambisol)	Inceptisol	Very young and shallow soil developed from Miocene marls. Contains calcium carbonate. Frequent stones. Well drained. Slope 4%.	Sunflower, *Helianthus annus* L.
Thermic, calcic, montmorillonitic, very fine Typic Haploxererts (Calcic Vertisol)	Vertisol	Valley bottom soil formed from blue marls of the Upper Tortoniens period and colluvium. Slope 1%	Faba beans *Vicia faba* L.

[a]USDA classification (FAO classification between brackets) from Del Campillo García et al. (1993).

for more than 10 years. Texture of the surface soils is given in Table 3. The soils had moderate organic matter contents, slightly alkaline pH, total iron oxide contents around

Table 3
Dispersed particle size distribution

	Texture class[a]	Particle size[b] (mm)						
		Clay <0.002	Silt 0.002–0.05	vfs 0.05–0.1	fs 0.1–0.25	ms 0.25–0.5	cs 0.5–1.0	vcs 1.0–2.0
		g kg^{-1} fine earth						
Red Alfisol	scl	268	230	159	78	82	107	76
Yellow Alfisol	scl	264	288	184	93	62	60	54
Fluvent	sl	161	348	222	105	63	46	40
Inceptisol	cl	383	272	116	51	48	61	69
Vertisol	c	537	370	38	18	15	14	8

[a]scl = Sandy clay loam, sl = sandy loam, cl = clay loam, c = clay.
[b]vfs = Very fine sand, fs = fine sand, ms = medium sand, cs = coarse sand, vcs = very coarse sand.

Table 4
Soil chemical characteristics
Standard error of mean between brackets.

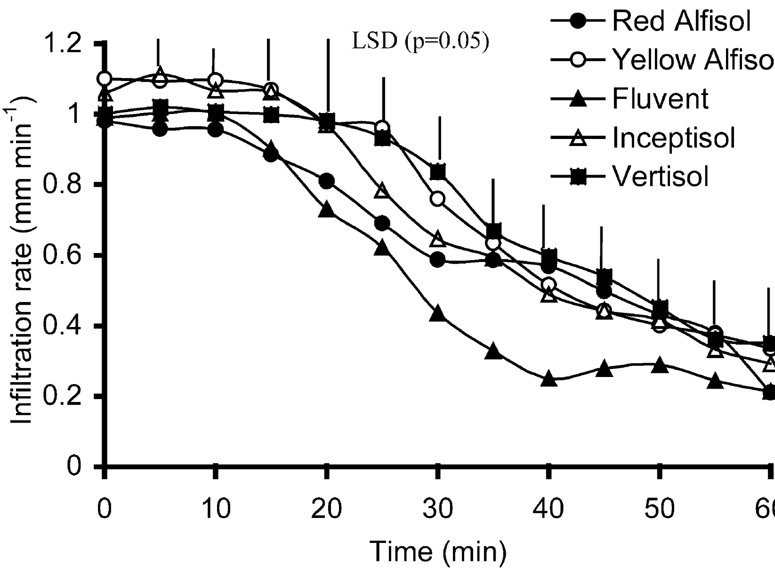
Soil	Organic matter (%)	pH (H_2O)	Fe_d ($\mu g\ g^{-1}$)	BS (%)	CEC ($cmol_c\ kg^{-1}$)	Ca^{2+} ($cmol_c\ kg^{-1}$)	Mg^{2+} ($cmol_c\ kg^{-1}$)	K^+ ($cmol_c\ kg^{-1}$)	Na^+ ($cmol_c\ kg^{-1}$)
Red	2.58	6.4	12,424	75	17.8	11.5	1.4	0.3	0.2
Alfisol	(0.11)	(0.11)	(605)		(0.23)	(0.34)	(0.22)	(0.00)	(0.00)
Yellow	2.83	6.8	9993	82	20.2	14.4	1.5	0.5	0.1
Alfisol	(0.05)	(0.02)	(607)		(0.20)	(0.53)	(0.03)	(0.00)	(0.00)
Fluvent	2.12	7.4	10,367	100	12.7	10.8	1.2	0.6	0.1
	(0.06)	(0.07)	(628)		(0.12)	(0.13)	(0.04)	(0.03)	(0.01)
Inceptisol	2.59	7.8	10,992	100	30.3	25.5	3.5	1.2	0.2
	(0.13)	(0.07)	(534)		(0.10)	(0.27)	(0.17)	(0.07)	(0.00)
Vertisol	3.11	7.7	7540	100	46.5	40.3	5.0	1.1	0.2
	(0.04)	(0.06)	(107)		(0.03)	(0.04)	(0.03)	(0.03)	(0.00)

10 g kg^{-1} Fe, and moderate to high CEC, with Ca^{2+} as the dominant cation on the exchange complex (Table 4).

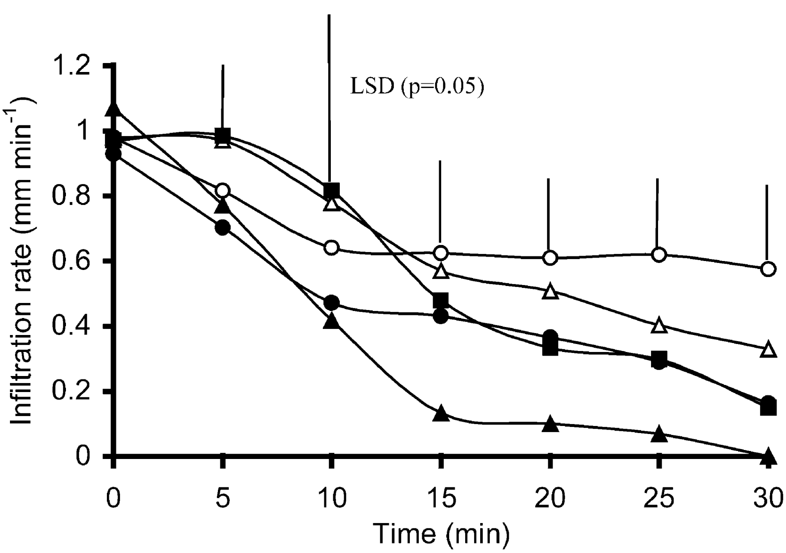
3.2. Infiltration

Cumulative infiltration during the dry run was highest in the Vertisol (77% of rainfall), moderate in the Yellow Alfisol (65%), Inceptisol (64%) and Red Alfisol (64%), and lowest in the Fluvent (53%). Cumulative infiltration during the 30-min wet run was 64% for the Yellow Alfisol, 60% for the Inceptisol, 52% for the Vertisol, 43% for the Red Alfisol and 25% for the Fluvent. Infiltration rates showed two different patterns among the soils studied (Fig. 3), following a strongly reversed “S” trend for the Fluvent in the 1 h dry run and a more gentle decrease in infiltration rates for the other soils. Infiltration rate of the Fluvent reached a steady state at 0.2 mm min^{-1} after 40 min of the dry run and decreased to 0.0 mm min^{-1} after 15 min of the wet run. This indicates that the Fluvent is prone to formation of a surface seal or has very low saturated hydraulic conductivity. The lower steady-state infiltration rate of the Fluvent at the end of the wet compared to the dry run may be due to residual swelling of clay minerals (L.D. Meyer, personal communication), or to the development of a multi-layered seal (West et al., 1992).

The time to incipient runoff in the dry run of the Vertisol was very long (24 min, Table 1). High infiltration in the dry run was likely due to subsurface cracks in this shrink-swell soil. In the wet run, however, infiltration rate in the Vertisol decreased rapidly, indicating that the cracks had closed overnight due to swelling. The fact that infiltration rate of the Vertisol did not stabilize during the 30-min wet run, suggests that it will decrease to less than 0.2 mm min^{-1} if the whole soil profile is saturated (a common feature in the Mediterranean winter season). Although the Inceptisol originated from the same parent material as the Vertisol and had similar color and clay mineralogy, more rapid decline of the infiltration rate during the dry run and a high infiltration rate



A



B

Fig. 3. Infiltration rates in dry (A) and wet (B) run. Bars above highest curve indicate LSD values ($p = 0.05$). Legend for both figures in graph A.

in the wet run of the Inceptisol indicate that this soil did not exhibit subsurface cracks, while its higher sand content favored higher infiltration in the wet run compared with the Vertisol.

The rapid decrease of infiltration rate of the Red Alfisol during the dry run may have been due to its higher antecedent moisture content compared with other soils. During the wet run, infiltration rate of this soil also decreased to low values, similar to that of the Vertisol, which was unexpected considering the sandy texture of this soil. Data from a nearby soil pit (Del Campillo García et al., 1993) showed, however, that clay content (smectitic) in the Bt horizon was 75%. Considering the low hydraulic conductivity of such a subsoil in a wet state, it is to be expected that infiltration rates can decrease to low values.

The infiltration behavior of the Yellow Alfisol was difficult to explain. Infiltration rates in the dry run were much lower than in the wet run. Overnight wetting of the soil matrix apparently led to higher infiltration rates in this soil. The only obvious difference between the Red and Yellow Alfisol was their iron oxide mineralogy. Iron oxide mineralogy, however, did not explain a higher infiltration rate in the wet run of the Yellow Alfisol. Water repellency may have played a role (Wallis and Horne, 1992), but was not determined. Soto and Díaz-Fierros (1998) reported severe water repellency in sandy soils in Spain having less than 12% volumetric water content.

3.3. Soil loss

Total soil loss in the dry run was higher for the Yellow Alfisol and Fluvent than for the Red Alfisol, Inceptisol, and Vertisol (Table 5). Soil loss in the wet run, however, did not differ significantly among the five soils studied. Differences in soil loss rate for each soil between dry and wet runs were significant only for the Vertisol. Soil loss doubled between dry and wet run for this soil. High wet-run soil loss of the Fluvent was due to

Table 5
Total soil loss for each soil type during dry and wet run

Soil	Dry run		Wet run		t-Test[a]
	Soil loss[b] g m^{-2} h^{-1}	S.E.[c]	Soil loss	S.E.	
Red Alfisol	527[b]	4.5	629[a]	15.2	ns
Yellow Alfisol	1203[a]	67.9	961[a]	218.2	ns
Fluvent	985[a]	104.8	1557[a]	402.3	ns
Inceptisol	605[b]	29.7	762[a]	36.1	ns
Vertisol	415[b]	57.9	824[a]	73.3	s
CV (%)		15.6		42.3	

[a]Two-sided Dry Run–Wet Run comparison with pairwise t-test ($p = 0.05$), s = significant, ns = nonsignificant.

[b]Values in a column followed by the same letter are not significantly different (Tukey's multiple range test, $p = 0.05$).

[c]Standard error of the mean.

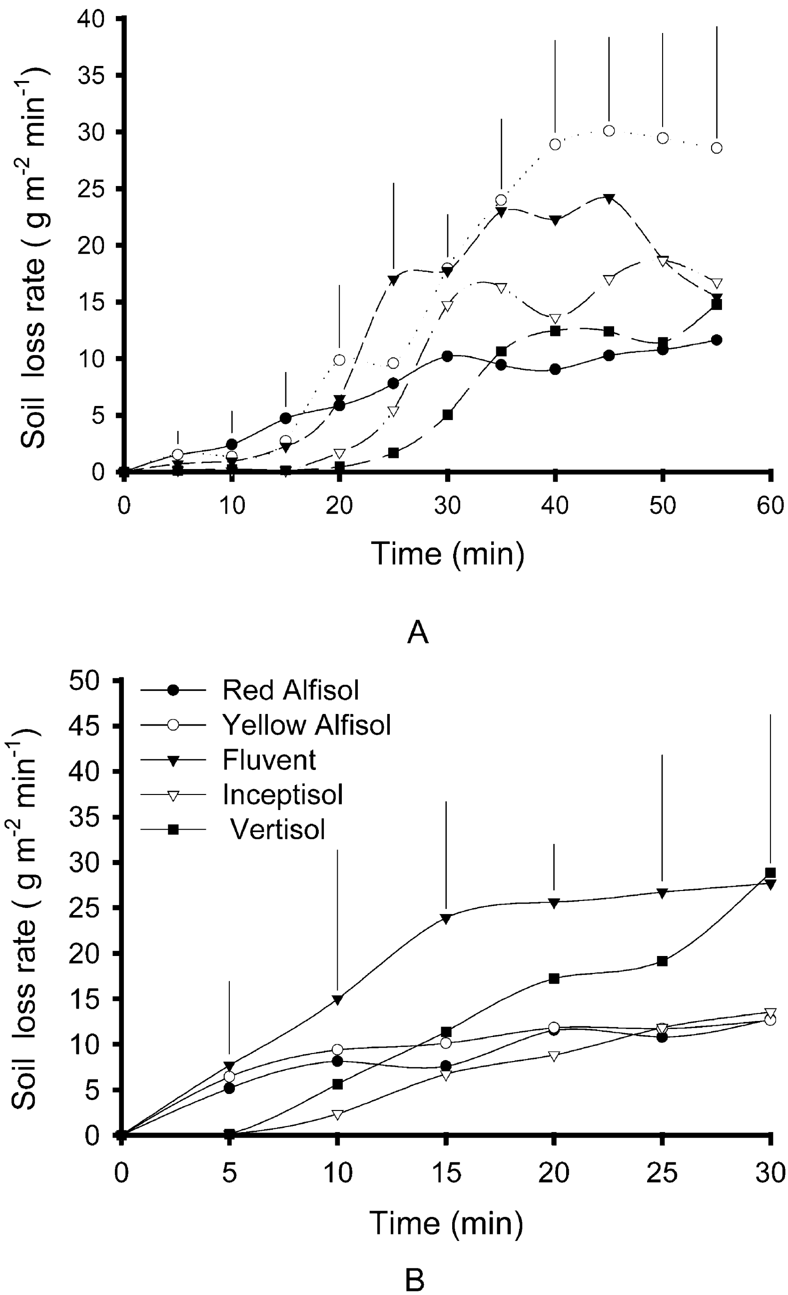


Fig. 4. Sedigraph of dry (A) and wet (B) run. Bars above highest curve indicate LSD ($p = 0.05$). Legend for both figures in graph B.

one replicate that had twice the soil loss of the other two replicates, resulting in a high standard error.

All dry run sedigraphs followed an "S" pattern (Fig. 4), in which three periods can be distinguished: (1) gradual increase, (2) strong increase, and (3) levelling off. During the first phase, soil loss was transport-limited by the lack of surface runoff. Soil particles were dislodged by splash but were not transported to the end of the interrill plot. During the second phase, splash losses were probably the result of slaking and increased air

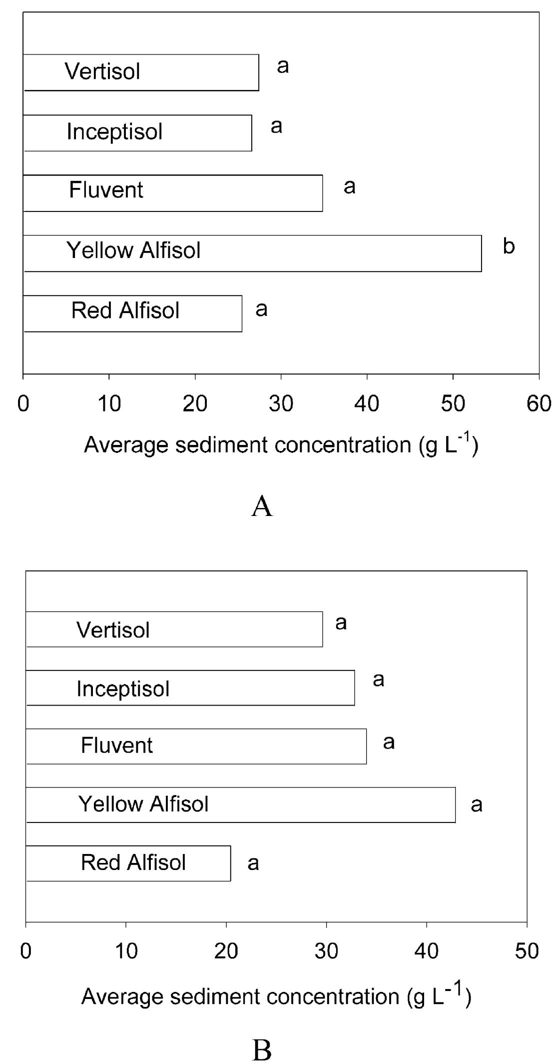


Fig. 5. Average dry (A) and wet (B) run sediment concentration. Bars followed by different letter are significantly different (Tukey's test, $p = 0.05$).

pressure inside submerged aggregates. The third phase was reached when unstable aggregates had slaked and the surface was smoothed.

Sediment transport started at the same time as runoff, early in the dry run of the Red Alfisol, later in the dry run of the Fluvent and Yellow Alfisol, and last in the dry run of the Inceptisol and Vertisol (Fig. 4A). The soil loss rate in the dry run increased to highest values on the Yellow Alfisol and Fluvent, while on the other soils it remained at a lower level. Soil-loss rate of the Red Alfisol, Inceptisol and Fluvent levelled off after 30–35 min into the dry run and after approximately 45 min in the Yellow Alfisol. It did not level off in case of the Vertisol (Fig. 4A). The inflection point in the wet run sedigraph occurred after 10 min for the Red and Yellow Alfisol, and after 15 min for the Fluvent (Fig. 4B). Soil-loss rate in the wet run continued to increase strongly in the Vertisol and less so in the Inceptisol. Sediment concentration of the Yellow Alfisol was significantly higher than that of the other soils in the dry run (Fig. 5A), but was not significantly higher in the wet run (Fig. 5B).

3.4. Use of empirical erodibility equations from the USA

Average dry- and wet-run soil-loss rates were negatively correlated with clay content, and positively with very fine sand and silt + very fine sand content (Table 6). The correlation between silt + very fine sand content and average soil loss was better than that between very fine sand content and soil loss. This may indicate that very fine sand content alone is not the best parameter to use to predict interrill erodibility (as is now the case in the WEPP soil erosion model). The correlation with organic matter content, Ca and Mg content was negative. These correlations correspond to those used to predict erodibility in the USLE, and to observed effects of organic matter on aggregate stability (Kemper and Koch, 1966; Wischmeier and Mannering, 1969; Tisdall and Oades, 1982).

The limited number of soil types used in this study did not allow differentiation between the influence of clay, organic matter content (OM), or Ca^{2+} and Mg^{2+}

Table 6
Simple linear correlation coefficients between soil properties and soil loss in dry run and wet run

	Soil loss		
	Dry run	Wet run	Average
Clay content	−0.70	−0.58	−0.71
Silt content	0.03	0.58	0.35
Very fine sand	0.77	0.60	0.77
Silt + very fine sand	0.72	0.98***	0.96***
New sand[a]	0.00	0.40	0.22
Organic matter	−0.36	−0.65	−0.57
Ca^{2+}	−0.37	−0.25	−0.34
Mg^{2+}	−0.67	−0.39	−0.59

[a] Total sand minus very fine sand.
*** Significant at $p < 0.001$.

Table 7
Measured and calculated WEPP interrill erodibility (WEPP-K_i)

	Dry run[a]	Wet run[a]	Average[a]	Calculated[b]
	WEPP-K_i (10^6 kg s m^{-4})			
Red Alfisol	1.51[a]	1.48[a]	1.50[a]	5.78[b]
Yellow Alfisol	3.16[b]	2.04[a]	2.77[b]	6.26[b]
Fluvent	2.06[a,b]	2.17[a]	2.11[a,b]	6.99[b]
Inceptisol	1.80[a,b]	1.64[a]	1.72[a,b]	4.96[b]
Vertisol	2.21[a,b]	2.43[a]	2.14[a,b]	3.09[b]

[a] Values in a column followed by different letters are significantly different (Tukey's test, $p = 0.05$).
[b] Indicates calculated and measured average WEPP-K_i are significantly different (paired t-test, $p = 0.05$).

concentrations because of the interactions among these factors. WEPP-K_i was significantly different among soils in dry runs only (Table 7). Dry run WEPP-K_i of the Yellow Alfisol was significantly higher than that of the Red Alfisol. Differences between these and the other soils were not significant, however. In the wet run, significant differences in WEPP-K_i disappeared. The average WEPP-K_i of dry and wet run of the Yellow Alfisol was significantly higher than that of the Red Alfisol. Differences between average WEPP-K_i of these and other soils were not significant. The primary reason for the lack of significant differences in erodibility was the high variability in the data. Additionally, the method of calculating WEPP-K_i resulted in low erodibility values for soils having high runoff rates. Consequently, the WEPP-K_i of the Vertisol in the wet run was lower than that in the dry run (Table 7), despite the soil loss being twice as high (Table 5). Estimated WEPP-K_i was up to four times higher than the K_i computed from the data (Table 7).

4. Discussion and conclusions

The Fluvent had most rapid decrease of infiltration rate among the soils of this experiment in both dry and wet run. Soil-loss rate of the Fluvent was highest, although it decreased rapidly 45 min after start of the dry run (Fig. 4A). In the wet run, one replicate of the Fluvent had much higher soil loss than the other replicates (Table 5, Fig. 4B). These observations suggest that a seal formed on this soil, first because a consolidated seal releases fewer soil particles, and second because seal failure would explain high soil loss in one replicate. Seal failure would not occur always at the same time for all replicates and would cause high soil loss compared to the replicates where the seal was still intact. The Fluvent was among the more erodible soils in this study due to its low infiltration capacity and relatively high soil loss.

Subsurface cracking of the Vertisol resulted in high infiltration rate (Fig. 3) and low soil loss (Fig. 4) in both dry and wet runs. Neither infiltration rate nor soil-loss rate of the Vertisol stabilized during this experiment. It is suggested, that, in a wet condition (common in Mediterranean winters), Vertisols will become highly impermeable and more erodible. Future rainfall simulation studies should be performed on wet soils for longer periods than 30 min until final infiltration rate stabilizes to confirm this.

The Inceptisol was similar to the Vertisol in parent material, color and clay mineralogy, but its higher sand content and shallow surface soil did not result in shrink–swell cycles and, therefore, infiltration rate remained high and soil-loss rate low at the end of the wet run. The Red Alfisol had comparable runoff and soil loss as the Inceptisol.

The Yellow Alfisol exhibited lower infiltration and soil loss in the dry compared to the wet run. Although the Red and Yellow Alfisols had similar texture and organic matter contents, they had very different soil loss and infiltration characteristics. Soil-loss rate of the Yellow Alfisol increased rapidly during the dry run, indicating that this soil was unstable during rapid wetting, which is confirmed by its high sediment concentration in the dry run (Fig. 5A). However, during the wet run infiltration rate decreased only slowly and stabilized at a high level. Sediment concentrations in the wet run were not significantly different among soils (Fig. 5B). The presence of hematite in the Red Alfisol can increase aggregate stability more than that of goethite in the Yellow Alfisol (Colombo and Torrent, 1991), which would explain the difference in soil-loss rates of the two soils. The goethite mineralogy of the Yellow Alfisol does not, however, explain the low soil-loss rate and high infiltration rate in the wet run. Water repellency is a more likely explanation. It has been observed in very dry soils of the Mediterranean region (Wallis and Horne, 1992; Soto and Díaz-Fierros, 1998). No measurements were made, however, to confirm that water repellency was the reason for low infiltration in dry run and high infiltration in wet run.

Soil loss was highly correlated to very fine sand content and silt + very fine sand content. Because very fine sand content is the factor used to calculate WEPP interrill erodibility, and silt + very fine sand content is the most important factor to calculate erodibility in the USLE, this suggests that erodibility of these soils is determined by similar soil properties as soils from North America.

The absolute magnitudes of soil loss and interrill erodibility observed in this study were, however, very different from those commonly reported for soils from the USA (Tables 5 and 7). Soil-loss rates ranging from 570 to 7000 g m^{-2} h^{-1} are reported in rainfall simulation studies on small plots in the midwestern US (Bajracharya et al., 1992) and the southern Mississippi valley (Meyer and Harmon, 1984). Although most rainfall simulation studies in the USA have been conducted on silt loam soils, soil-loss rates reported for clayey and sandy soils from the USA are still higher than those measured in the present study. Low soil loss was also reported by Kutiel et al. (1995) on a Terra Rossa soil in Israel, Böhm and Gerold (1995) on a calcic Ochrept and a Xeroll in Turkey, and Díaz-Fierros et al. (1987) on soils in northwest Spain 12 months after burning. Edeso et al. (1999) reported low soil loss on little disturbed but highly sloping Cambisols in north Spain.

Reasons for the apparently low erodibility of the soils of this study may be very stable aggregation or high infiltration. Organic matter contents were rather high for the soils of this region. Soil organic matter contents rarely exceeded 10 g kg^{-1} in other studies in the valley of the Guadalquivir river (Paneque and Clemente, 1974a,b; Clemente Salas et al., 1977a,b; Paneque Guerrero et al., 1977). This factor may have increased aggregate stability, infiltration and resistance to erosion of these soils. High concentration of polyvalent cations (especially Ca^{2+}) is another factor that stimulates flocculation of soil colloids and increased resistance to erosion, and this may have been a factor in the soils with high Ca saturation (Inceptisol and Vertisol). Finely divided carbonate content has been proposed as a stabilizing factor in Mediterranean soils (De Meester and Jungerius, 1978), but was not determined in this study. It is not expected, however, that carbonate content played a role in the resistance to erosion of the Red and Yellow Alfisols because their measured pH was below 7 (Table 4). Additionally, very low aggregate stability of the surface soil of similar Alfisols from the region suggests that exchangeable Ca is not an important factor determining erodibility of sandy surface soils in this region (unpublished results of the senior author).

Infiltration rates measured in this study were high compared with those reported by Meyer and Harmon (1984) for rainfall simulation studies in the US, but agreed with high infiltration rates reported in other studies in the Mediterranean region (De Meester and Epping, 1979; Kutiel et al., 1995; Wainwright, 1996; Soto and Díaz-Fierros, 1998).

It seems, therefore, that the high infiltration rate and moderately high organic matter contents of the soils of this study are the primary reasons for their low erodibility. It is possible that the subsoil was not thoroughly wetted in the 1-h dry run. In the rainy winter season, infiltration rates may, therefore, be lower than the average infiltration rates measured in this study. Kosmas et al. (1997) reported an increase in runoff and erosion in the wetter Mediterranean regions, probably due to decreasing infiltration rates in wet soils.

The equation to calculate interrill erodibility in the WEPP erosion model significantly overestimated measured interrill erodibility (Table 7). It is, therefore, recommended that the equations to calculate K_i in the WEPP model be revised for the soils of the Mediterranean region based on rainfall simulation studies in this region. At present, it appears that erodibility of Mediterranean soils will be significantly overestimated in the WEPP model. Although previous studies have shown that the rainfall simulator of this study produces similar raindrop distribution as the WEPP rainfall simulator, the conclusions need to be verified with a rainfall simulator mounted with oscillating or rotating Veejet 80100 nozzles. It is also recommended to use a range of rainfall intensities in future studies, for example, 30, 60 and 120 mm h^{-1}.

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